



Klaus Keller and Rob Lempert
have given me the title:

Beyond Cost Benefit Analysis



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But first...

...indulge me 3-4 minutes on two topics that came up yesterday on which I *have* actually done some real work:

Carbon Capture and Geological Sequestration (CCS)

Solar Radiation Management (SRM)

A few years ago...

...we concluded that while the technology for CCS is critically important, so too is developing a U.S. regulatory regime that assures CCS will be done in a manner that is safe, environmentally sound, affordable, compatible with evolving international carbon control regimes (including emissions trading) and socially equitable.

To help make this happen we launched a collaborative effort called the CCSReg Project.



The screenshot displays the CCSReg.org website. The header features the URL www.CCSReg.org and the title "CCS Reg" above a large image of an industrial facility. A navigation bar includes links for Project Team, Why CCS?, Approach, Publications, Resources, State Policy, and Home. The main content area is titled "CCSReg Project" and contains text about the need for CCS technology to reduce CO₂ emissions by 80% by 2050. It mentions a workshop held in Washington, DC, on October 25 & 26, 2010, and a policy brief released on May 19, 2010. A sidebar on the right, titled "project news", provides more details about these events. The footer notes that the CCSReg project maintains a website.

www.CCSReg.org

CCS Reg

photo courtesy of Øyvind Røgen / StatoilHydro

Project Team Why CCS? Approach Publications Resources State Policy Home

CCSReg Project

Avoiding catastrophic climate change over the coming decades will require the entire world to reduce its emissions of CO₂ by roughly 80%. In the long run, new—perhaps unimaginable—technologies may allow us to sustain such a low-carbon future without the use of coal, oil and natural gas (fossil fuels). However, for at least the next half century, there does not appear to be any way to sustain modern society and allow the rest of the world to develop rapidly without continued use of fossil fuel.

Fortunately CO₂ can be captured from power stations (and similar large industrial plants) before it enters the atmosphere and safely disposed a half mile or more (> 1 km) underground in appropriate geological formations. This technology is called carbon

photo courtesy of Dag Myrnes / StatoilHydro

project news

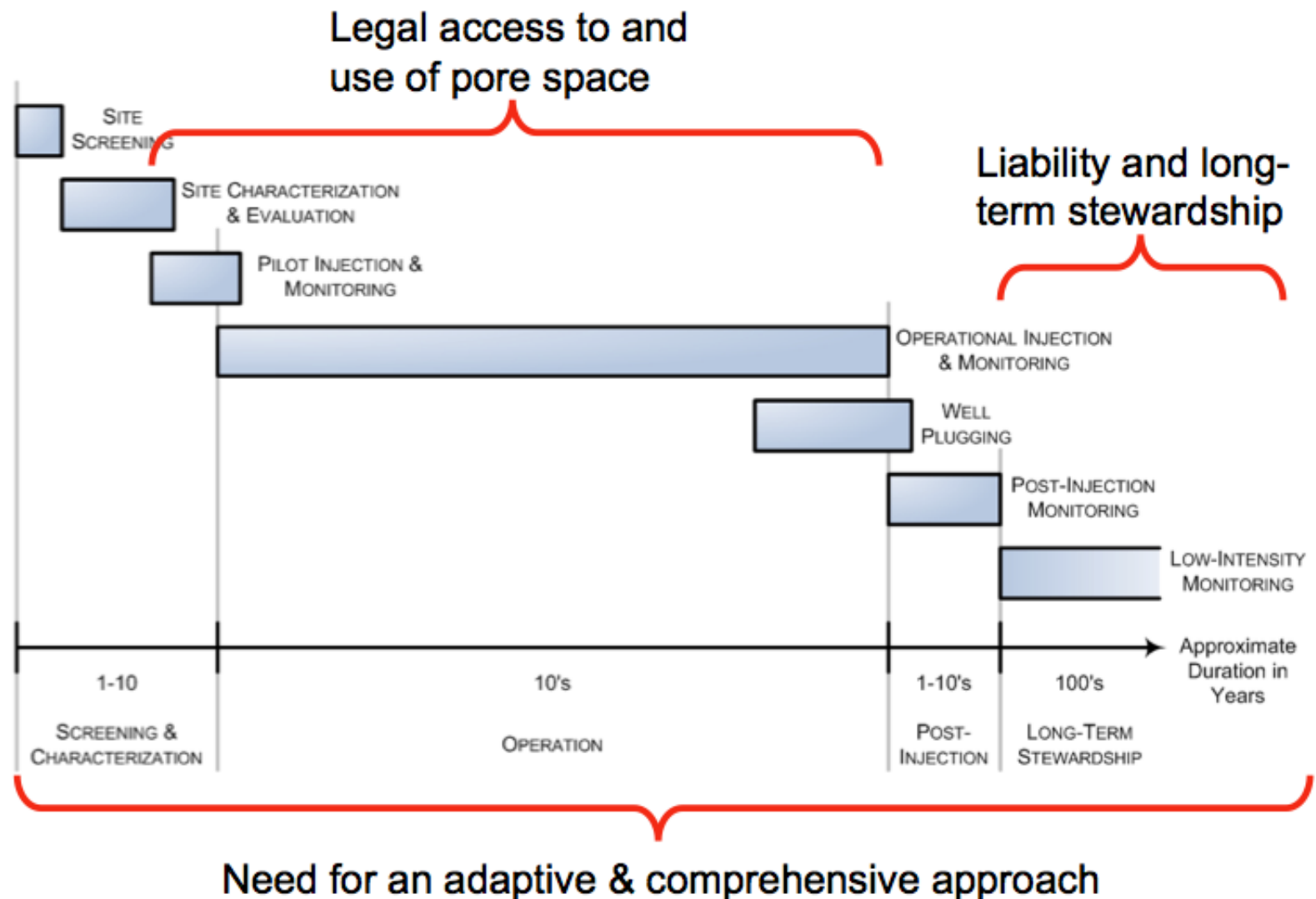
On October 25 & 26, 2010, the CCSReg project held a workshop on regulation of CCS in Washington, DC. Presentations from the workshop and a summary of comments are [available](#).

On May 19, 2010 the CCSReg project released [model legislation](#) that implements the recommendations made in the policy briefs.

A [summary of recommendations](#) made in the policy briefs is also available.

The CCSReg project maintains a

We developed policy briefs to address:



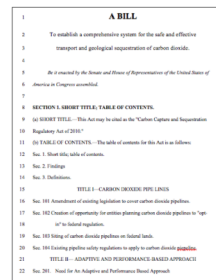
We did extensive briefings...



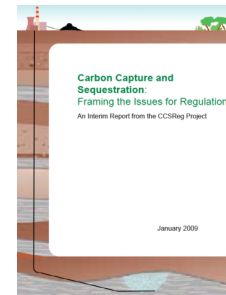
...on Capitol Hill, at EPA, to industry and environmental groups both in the U.S. and internationally. Also organized several workshops and made a variety of conference presentations, all with the dual objectives of getting our ideas out and obtaining critical input.

While we got very favorable reactions, and lots of useful advice, it soon became clear that nobody on the Hill was going to pick up these ideas and convert them to legislative language...

...since we had a couple of experienced lawyers on our team we did it ourselves.



50-pg. draft legislation



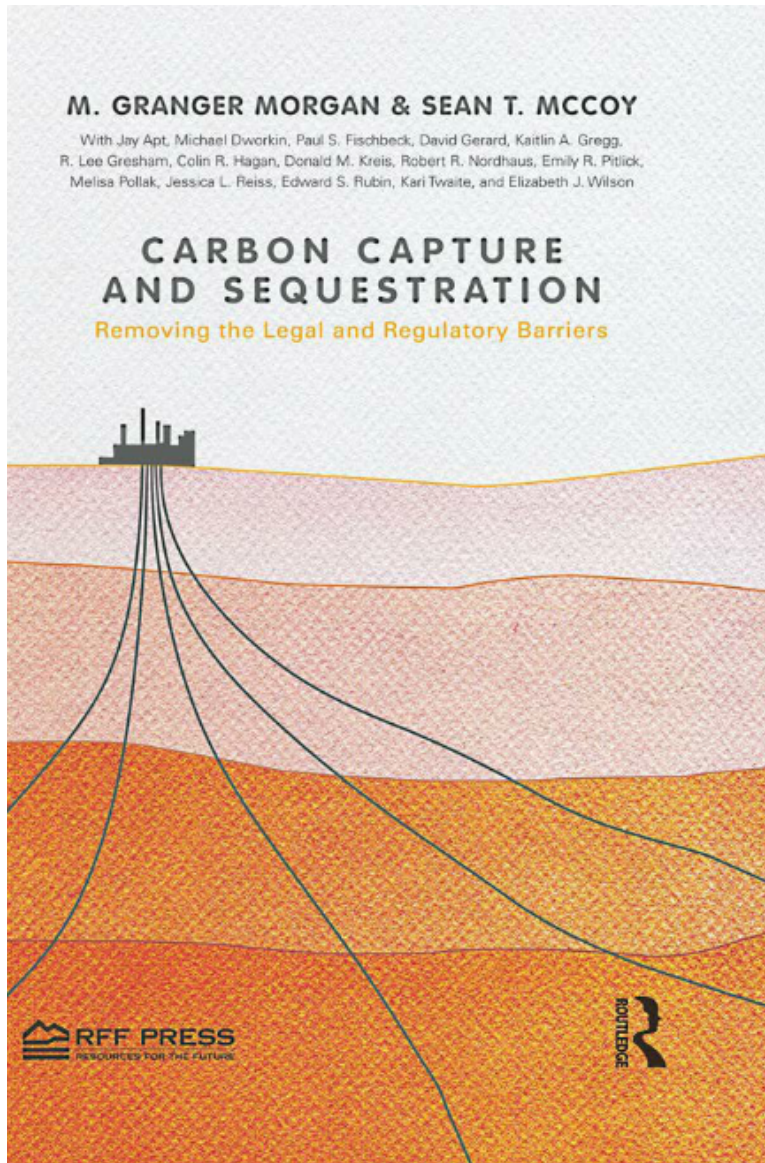
Interim report



Six policy briefs

In June 2012...

...we published a book through RFF Press.



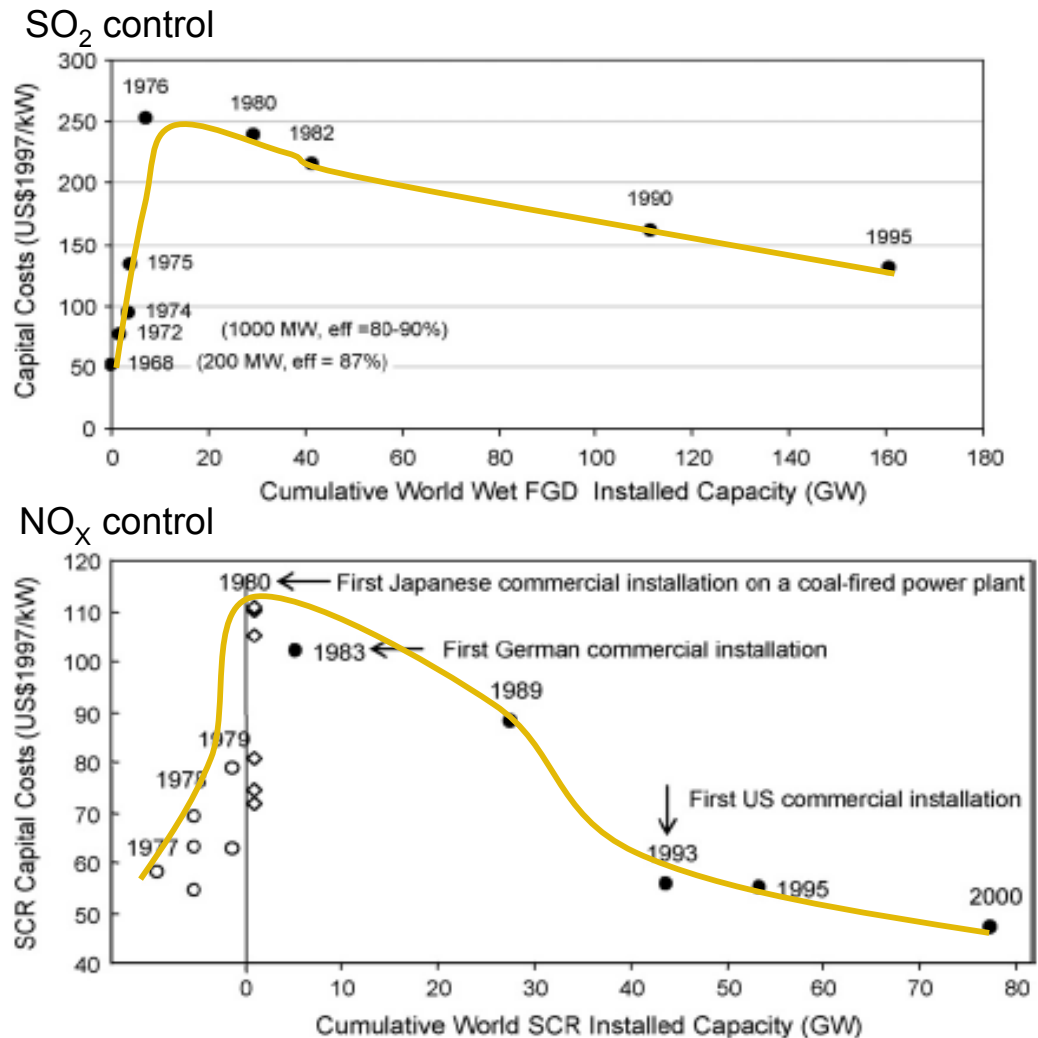
Contents

1. The Importance of CCS in a Carbon Constrained World
2. Technology for Carbon Capture and Geologic Sequestration (CCS)
3. Siting CO₂ Pipelines for Geologic Sequestration
4. Permitting Geological Sequestration Sites
5. Learning from and Adapting to Changes in Geologic Sequestration Technology
6. Access to Pore Space for Geological Sequestration
7. Liability and the Management of Long-term Stewardship
8. Greenhouse Gas Accounting for CCS
9. Making CCS a Reality
10. Conclusions and Recommendations

One figure from Chapter 9

In the case of both SO₂ scrubber technology and in the case of NO_x control technology, Ed Rubin finds that costs rose significantly after problems were encountered with the design and performance of the first few plants.

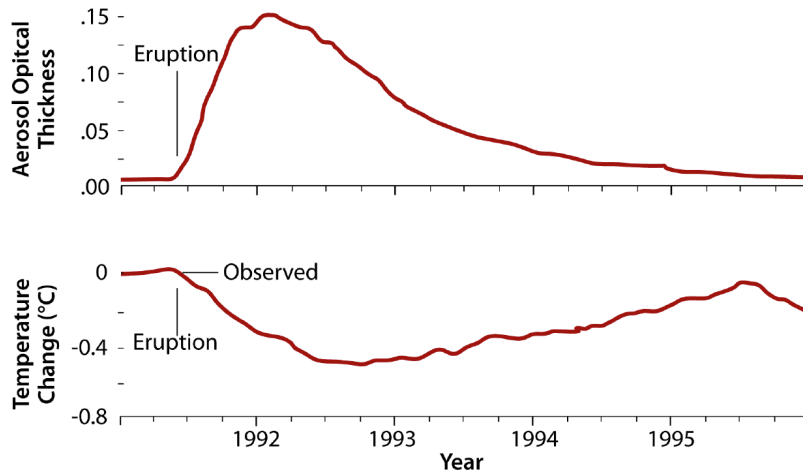
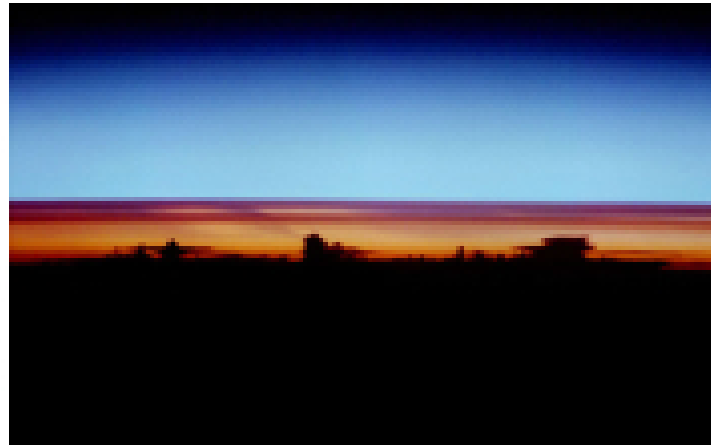
There is every reason to believe that the same will be true for CCS.



Source: Rubin et al., IJGGC, 2007.

SRM

Experience with large volcanic explosions make it clear that cooling can be very rapid.



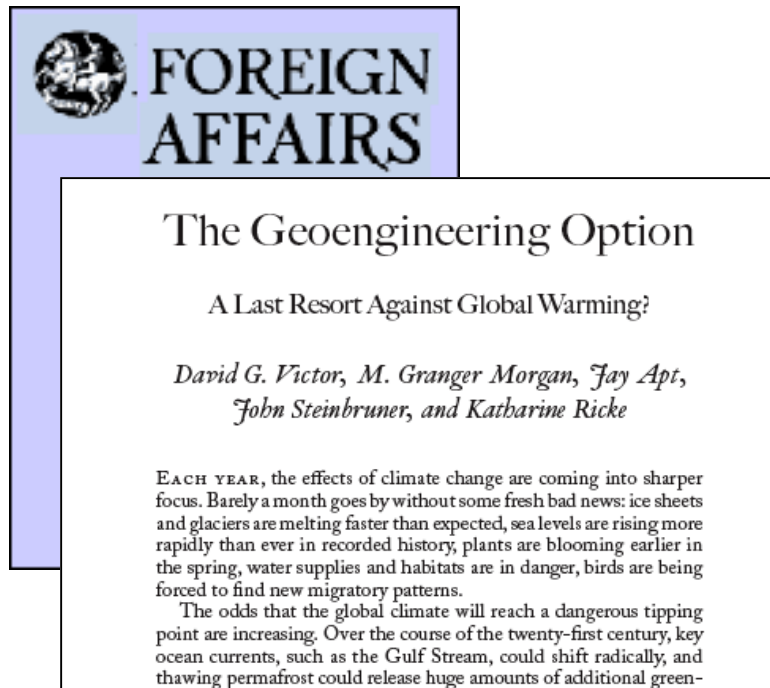
We looked at SRM in our first NSF climate center but then moved on...

The CFR workshop...

Because the diplomatic community was almost completely unaware of SRM, in 2008 I organized a workshop at the Council on Foreign Relations in Washington, DC.



The workshop led to a paper that appeared in the 2009 March/April issue of *Foreign Affairs*.



Participants in the 2008 workshop were all from North America.

To extend the conversation to a more international group, we ran a second workshop in April 2009 in Lisbon, Portugal.

Source: Council on Foreign Relations

The Lisbon Workshop...

...was hosted by the Ministry of Science, Technology and Higher Education of the Government of Portugal. The two-day workshop was held at the facilities of the Gulbenkian Foundation.



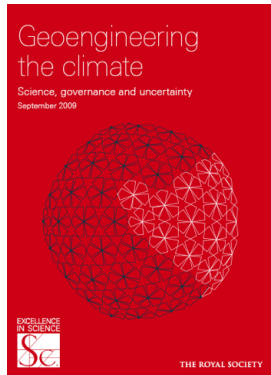
Co-sponsors included: IRGC, CMU-CDMC, U Calgary. Participants came from N. America, EU, China, Russia, and India.



Sources:
Gulbenkian & Qian Yi

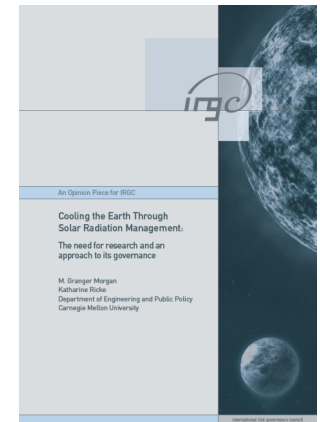
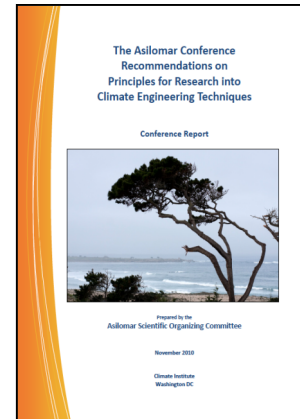


Some subsequent events...



Sep. 2009: The governance section of the Royal Society's report on Geoengineering

March 2010: The discussion of risk governance at the Asilomar conference on geoengineering



June 2009: U.S. NRC workshop on geoengineering



March 2010: Testimony to a joint session of the U.S. House Science Committee and the Science Committee of the UK Parliament



November 2010: IRGC opinion piece on governance



Geoengineering Options to Respond to Climate Change: Steps to Establish a Research Agenda

March 2010: Evening briefing to CFR

August 2010: First multi-university summer study



SRM...(Cont.)

March 2011:
SRMGI Kavli Center



June 2011: Lima IPCC expert
meeting on geoengineering

October 2011:
BPC report on
U.S. research



April 2012: CMU
workshop on managing
knowledge

May 2012:
DC CIT event

Jan 2011

January 2011: La Jolla
IGBP workshop
on ecosystem
impacts of
geoengineering



Paper now in press
at *AMBIO*

August 2011:
Second multi-
university summer
study program for
graduate students
and other young
investigators held
at Banff

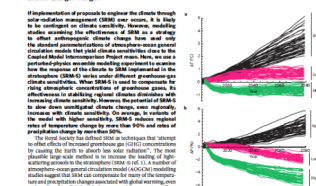


Jan 2012



Effectiveness of stratospheric solar-radiation
management as a function of climate sensitivity

Katherine L. Erickson^{1,2}, Daniel J. Rowlands¹, William J. Ingram^{1,3}, David W. Keith^{1,4}
and M. Gernig Mörner¹



Solar radiation management:
the governance of research

SRM...(Cont.)

Needed: Research Guidelines for Solar Radiation Management

M. GRANGER MORGAN
ROBERT R. NORDHAUS
PAUL GOTTLIEB

As this approach to geoengineering gains attention, a coordinated plan for research will make it possible to understand how it might work and what dangers it could present.

Emissions of carbon dioxide (CO₂) and other greenhouse gases (GHGs) continue to rise. The effects of climate change are becoming ever more apparent. Yet prospects for reducing global emissions of CO₂ by an order of magnitude, as would be needed to reduce threats of climate change, seem more remote than ever.

When emissions of air pollutants, such as sulfur dioxide and oxides of nitrogen, are reduced, improvements occur in a matter of days or weeks, because the gases quickly disappear from the atmosphere. This is not true for GHGs. Once emitted, they remain in the atmosphere for many decades or centuries. As a result, to stabilize atmospheric concentrations, emissions must be dramatically reduced. Further, there is inertia in the earth-ocean system, so the full effects of the emissions that have already occurred have yet to be felt. If the planet is to avoid serious climate change and its largely adverse consequences, global emissions of

GHGs will have to fall by 80 to 90% over the next few decades.

Because the world has already lost so much time, and because it does not appear that serious efforts will be made to reduce emissions in the major economies any time soon, interest has been growing in the possibility that warming might be offset by engineering the planet: a concept called geoengineering. The term solar radiation management (SRM) is used to refer to a number of strategies that might be used to increase the fraction of sunlight reflected back into space by just a couple of percentage points in order to offset the temperature increase caused by rising atmospheric concentrations of CO₂ and other GHGs. Of these strategies, the one that appears to be most affordable and most capable of being quickly implemented involves injecting small reflective particles into the stratosphere.

There is nothing theoretical about whether SRM could cool the planet. Every time a large volcano explodes and injects tons of material into the stratosphere, Earth's average temperature drops. When Mount Pinatubo exploded in

SPRING 2013 37

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March 27, 2013
POSTSCRIPT

The Truth About Geoengineering

Science Fiction and Science Fact

David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, Katharine Ricke
DAVID G. VICTOR is a professor at the School of International Relations and Pacific Studies and co-director of the School's new Laboratory on International Law and Regulation. M. GRANGER MORGAN is a professor and head of the Department of Engineering and Public Policy at Carnegie Mellon University. JAY APT is a professor and director of the Carnegie Mellon Electricity Industry Center. JOHN D. STEINBRUNER is a professor and director of the Center for International and Security Studies at the University of Maryland. KATHARINE RICHIE is a postdoctoral fellow at Carnegie Institution for Science.



Officials prepare to seed clouds near Bangkok, 2007.

Royal Thai Air Force rainmakers hoped to coax rains to clear away thick smoke from forest fires and stubble burning. (Sakree Subplang/Courtesy Reuters)

The failure to make much progress at the UN Climate Change Conference in Doha, Qatar this winter was yet another reminder that the world might soon face extreme climate shifts. In response, it is becoming increasingly likely that governments will adopt risky strategies, known as "geoengineering," to rapidly cool the planet. Four years ago, in order to raise awareness about geoengineering, we published "The Geoengineering Option [1]" in *Foreign Affairs*. Almost nobody thought that such tactics — which included spraying particles into the upper

CURRENT PROJECTS System

THE NATIONAL ACADEMIES
Advisors to the Nation on Science, Engineering, and Medicine

Committee Membership Information

Project Title:	Geoengineering Climate: Technical Evaluation and Discussion of Impacts
PIN:	DELS-BASC-12-04
Major Unit:	Division of Behavioral and Social Sciences and Education Division on Earth and Life Studies
Sub Unit:	Board on Environmental Change and Society Ocean Studies Board Board on Atmospheric Sciences & Climate
RSO:	Dunlea, Edward
Subject/Focus Area:	Earth Sciences; Engineering and Technology

Committee Membership
Date Posted: 04/25/2013

SRM

David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, and Katharine Ricke, "The Geoengineering Option," *Foreign Affairs*, 88(2), 64-76, March/April 2009.

Katharine Ricke, M. Granger Morgan and Myles R. Allen, "Regional Climate Response to Solar-radiation Management," *Nature Geoscience*, 3, 537-541, 2010.

David W. Keith, Edward Parson and M. Granger Morgan, "Research on Global Sun Block Needed Now," *Nature*, 463(28), 426-427, January 2010.

M. Granger Morgan and Katharine Ricke, *Cooling the Earth Through Solar Radiation Management: The need for research and an approach to its governance*, The International Risk Governance Council (IRGC), 24pp., 2010.

Katharine L. Ricke, Daniel J. Rowlands, William J. Ingram, David W. Keith and M. Granger Morgan, "Effectiveness of Stratospheric Solar-Radiation Management as a Function of Climate Sensitivity," *Nature Climate Change*, 2, 92-96, February 2012.

Lynn M. Russell et al., "Ecosystem Impacts of Geoengineering: A review for developing a science plan," *Ambio: A Journal of the Human Environment*, 41, 350-369, 2012.

David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, and Katharine Ricke, "The Truth About Geoengineering," Postscript, *Foreign Affairs*, 2013 Mar 27.

M. Granger Morgan, Robert R. Nordhaus, Paul Gottlieb, Needed: Research Guidelines for Geoengineering, *Issues in Science and Technology*, Spring 2013, pp 37-44.

BUT...

...I'm supposed to be talking about B-C
in the context of sea level rise and other
impacts from climate change.

At this point in my presentation at Snowmass I included four photos showing sea level rise that were commissioned by Dan Shrag. He has kindly provided them to me, but I do not feel comfortable sharing machineable copies.

The obvious first question is:

Benefit-Cost Analysis for what? Here are six possibilities:

1. Decisions by potentially affected parties (e.g., Port of Long Beach) about what investments to make to deal with likely future impacts from sea level rise.
2. Choices at the national level between alternative adaptive strategies such as sea walls *versus* coastal retreat.
3. Choices by a nation as to whether and how much emissions abatement to undertake.
4. Choices by a nation as to whether or not to join an international agreement on emissions abatement.
5. Assessment of the "social cost of carbon."
6. Choice of a globally optimum level of emissions abatement.

Example 1:

Decisions by potentially affected parties (e.g., Port of Long Beach) about what investments to make to deal with likely future impacts from sea level rise.

Use of B-C:

It is entirely appropriate to use a B-C formulation when a single decision maker (or a group that has shared values) is trying to decide if the costs of making some investment to mitigate the impacts of possible sea level rise (e.g., changing the dock facilities in Long Beach, CA) are greater or less than the benefits (in the form of reduced damages) that can be expected over the life of the project. Of course, given the high level of uncertainty one may want to use "robust decision making" techniques, but that is not at odds with a B-C formulation.

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I will explain why I say this in a moment, but first let's look at Example 2.

Example 2:

Choices at the national level between alternative adaptive strategies such as sea walls *versus* coastal retreat.

Use of B-C:

Analysis in this case involves several challenging issues:

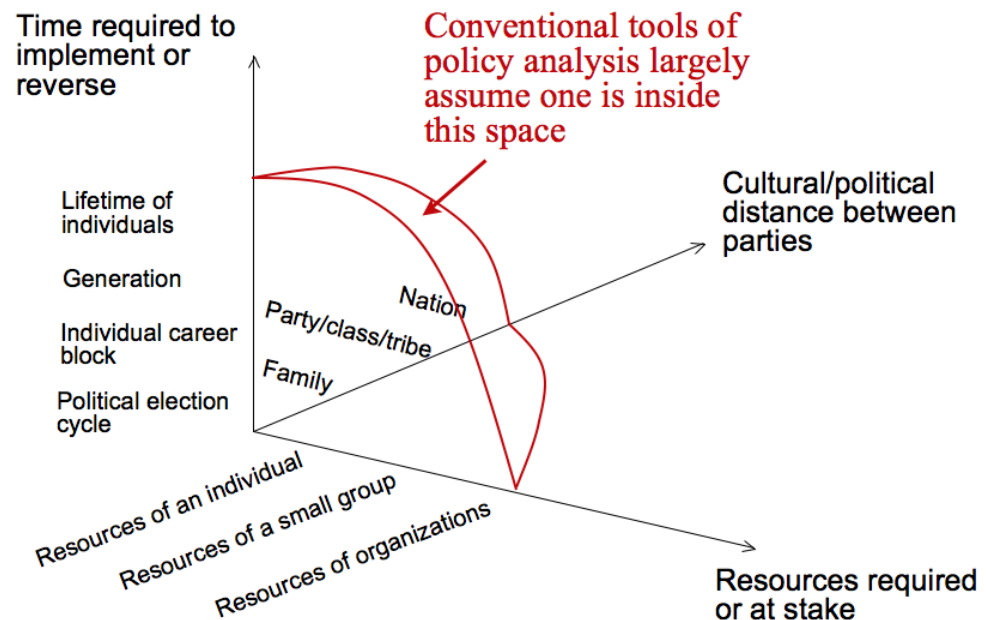
- Building stochastic storm damage models (most early damage will come from storms, not inundation);
- Assessing social values;
- Addressing issues of time preference (it would be desirable to do comparative analysis using several strategies, not just exponential or hyperbolic discounting).

Again, it would probably be desirable to use "robust" methods to search the space of options. However, again I believe this is a case where a nation could appropriately use a B-C formulation to inform its choices.

Why is B-C appropriate...

...as a strategy for Examples 1 and 2?

While the time-scale may be longer than for some B-C calculations, and there are various other analytical complications, both these examples fall squarely in the space in which the underlying assumptions made by conventional tools of policy analysis, including B-C, are valid.



Most conventional tools of policy analysis assume that:

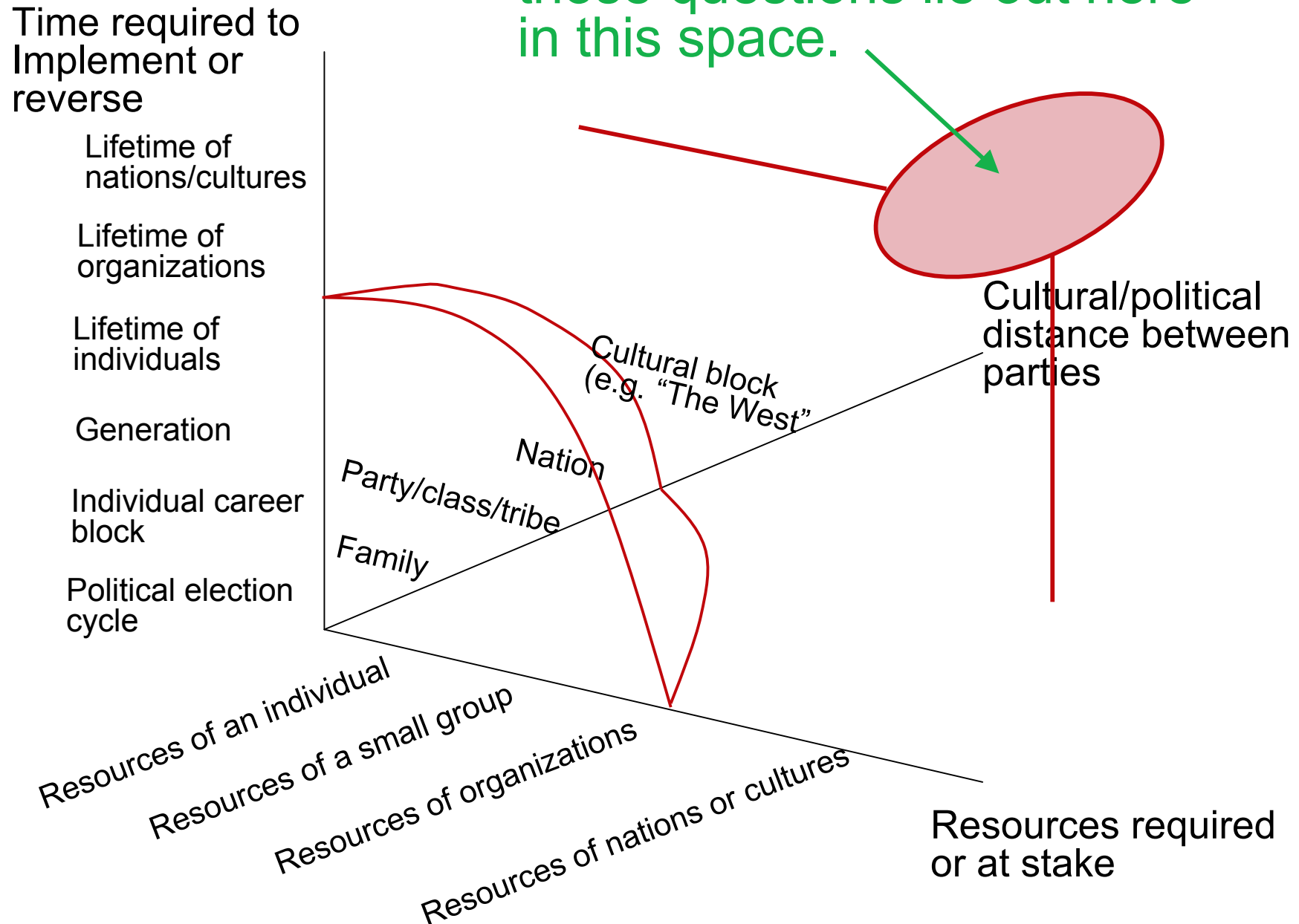
1. there is a single (public-sector) decision maker who faces a single problem (in the context of a single polity);
2. values are known (or knowable), static, and exogenously determined;
3. the decision maker should select a policy by maximizing expected utility;
4. the impacts involved are of manageable size and can be valued at the margin;
5. time preference is accurately described by conventional methods for assessing future costs and benefits;
6. the system under study can reasonably be treated as linear;
7. uncertainty is modest and manageable.

Because Examples 3 and 4...

...are more complicated, let me come back to them in a few minutes and next consider examples 5 and 6, where in my view the use of B-C methods is *not* appropriate. To remind you:

5. Assessment of the "social cost of carbon."
6. Choice of a globally optimum level of emissions abatement.

At least some aspects of those questions lie out here in this space.



That is because:

1. There is a single (public-sector) decision maker who faces a single problem (in the context of a single polity).



1. There is no single decision maker for the entire planet. Rather there are multiple decision makers who face multiple problems (in the context of different polities).

That is because:

2. Values are known (or knowable), static, and exogenously determined.



2. Values are diverse across parties, and likely to change over time and across generations (e.g., some may decide they like some of the changes, some may learn that the changes are much worse than expected; I don't want to see a change in the white pine, sugar maple, beach, and birch ecosystem of NH but my great great grandchildren may be very happy with a verdant mix of yellow pine and oak).

That is because:

3. The decision maker should select a policy by maximizing expected utility.



3. As noted above, there is no single global decision maker nor is there any single global utility function that all the world accepts that can be maximized.

That is because:

4. The impacts involved are of manageable size and can be valued at the margin.



4. Some of the impacts involved will be very large (for at least some parties) and so can not be valued at the margin (consider for example small island states that disappear under water).

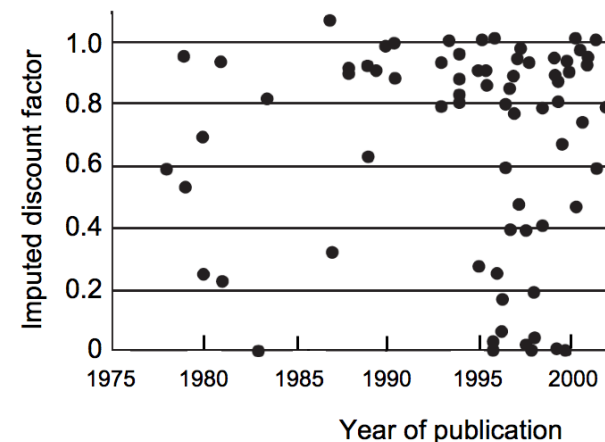
That is because:

5. Time preference is accurately described by conventional methods for assessing future costs and benefits.



5. Time preferences are likely to be very different for different parties, and in many cases not exponential or even hyperbolic.

Here, for example, are implicit discount factors from behavioral studies just among U.S. respondents:



That is because:

6. The system under study can be reasonably treated as linear.



6. The system under study is obviously highly non-linear and includes various positive and negative feedbacks.

That is because:

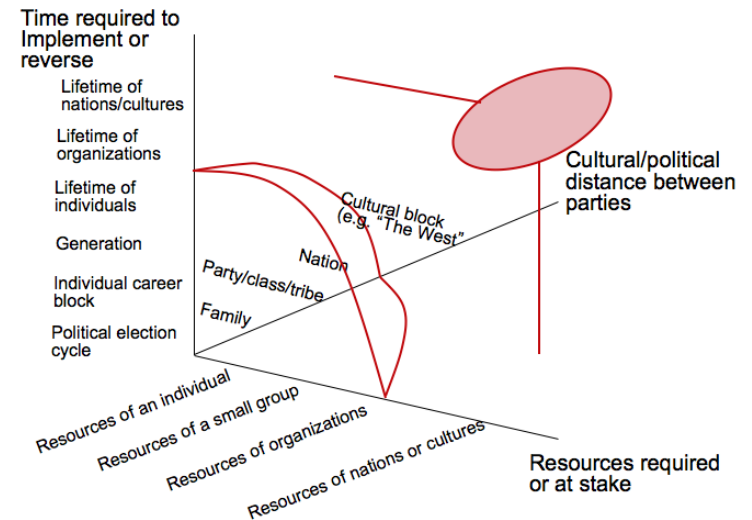
- 7. Uncertainty is modest and manageable.



- 7. Uncertainty is *very* large, and there are both known and almost certainly important unknown unknowns.

Bottom line

Before picking up any of the conventional tools of policy analysis (including B-C) and applying them to a climate problem, one really needs to think carefully about where important parts of the problem lie in this space. If they lie outside the “conventional zone,” it is likely that one will need to adopt (or develop) non-conventional analytical methods.



Problem 5.

Assessment of the "social cost of carbon."

Why do we need this?

Answer: Primarily because here in the U.S. some number is needed as agencies decide what carbon abatement investments they should make or how to value the carbon emissions of their projects.

Because of Executive Order 12866, the U.S. recently went through a great deal of numerology in order to get some numbers.

The purpose of the "social cost of carbon" (SCC) estimates presented here is to allow agencies to incorporate the social benefits of reducing carbon dioxide (CO₂) emissions into cost-benefit analyses of regulatory actions that have small, or "marginal," impacts on cumulative global emissions... (EPA, 2009)

Over the course of 50 pages...

...EPA (2009) performed a variety of reviews and calculations in an effort to cost out things like agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services. The report does not cover all the impacts of climate change, nor is it adequately international or come to grips with the possibility that we may end up in a "high tail" of one of the distributions of impacts. However, in my view, Anthoff and Tol (2010) identify the central issue:

Estimates of the marginal damage costs of carbon dioxide emissions require the aggregation of monetised impacts of climate change over people with different incomes and in different jurisdictions. Implicitly or explicitly, such estimates assume a social welfare function and hence a particular attitude towards equity and justice.

Source: Anthoff, D. and R. S.J. Tol (2010). "On International Equity and National Decision Making on Climate Change," *Journal of Environmental Economics and Management*, 60(1), 14-20.

Problem 6.

Choice of a globally optimum level of emissions abatement.

Why do we need this?

Answer: It is not clear to me that we do. Some would argue we need it in order to decide how much abatement the world should buy. However, even if such an analysis made sense (I'll argue in a moment that it does not), the obvious question is how, and by who, would the result be used?

Problem 6. Choice of a globally optimum level of emissions abatement.

Why do we need this?

Answer: It is not clear to me that we do. Some would argue we need it in order to decide how much abatement the world should buy. However, even if such an analysis made sense (I'll argue in a moment that it does not), the obvious question is how, and by who, would the result be used?

While it vastly oversimplifies, the following helps to explain my argument.

GHG Management from the top down.

Perform an IA in order to determine the "optimal" level of abatement.

Through international negotiations get a global agreement in place that endorses that level.

Persuade all major emitters to "sign up" and adopt coordinated policies to meet that level.

GHG Management from the bottom up.

Different parts of the world get serious about reducing emission of GHGs at different times.

Each starts doing various things to reduce emissions.

As more get serious, international negotiations begin to work to coordinate the several abatement regimes.

GHG Management from the top down.

The key thing...

...needed to implement this model is integrated assessment that determines the target.

Perform an IA in order to determine the "optimal" level of abatement.

Through international negotiations get a global agreement in place that endorses that level.

Persuade all major emitters to "sign up" and adopt coordinated policies to meet that level.

GHG Management from the bottom up.

The key thing...

...needed to implement this model is emission abatement supply curves so that those who choose to get started can do so in the most cost effective way.

Different parts of the world get serious about reducing emission of GHGs at different times.

Each starts doing various things to reduce emissions.

As more get serious, international negotiations begin to work to coordinate the several abatement regimes.

If and when we manage...

...to begin to get serious control of GHG emissions from major emitting countries, my money is on it happening according to Model 2 (i.e., bottom up).

At that point what will be most needed is clear evidence of what abatement strategies are most cost-effective.

It is for this reason that our latest distributed NSF center is called the Center for Climate and *Energy* Decision Making and is primarily focused on finding ways to decarbonize the energy system.

If and when we manage...

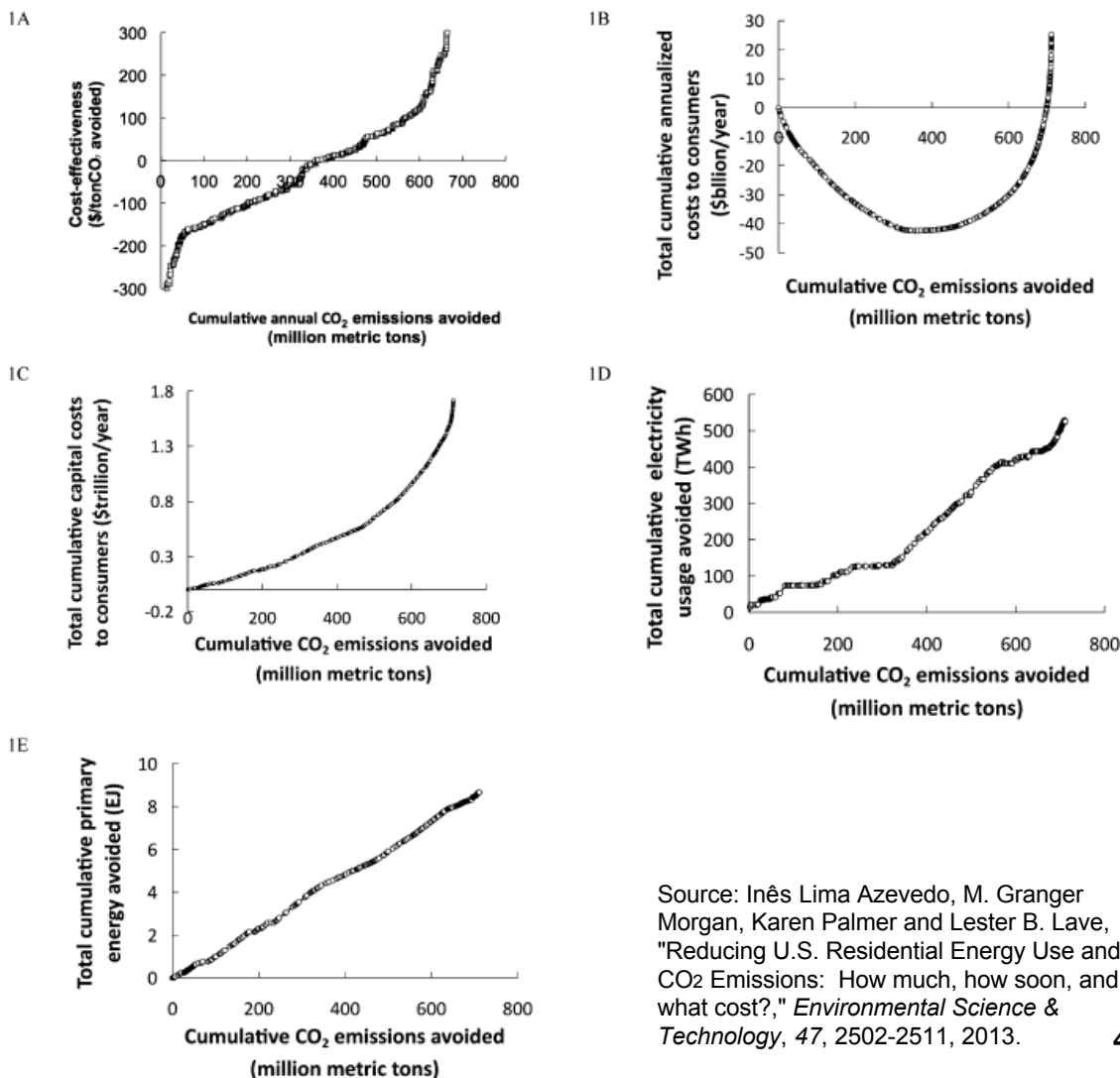
...to begin to get serious control of GHG emissions from major emitting countries, my money is on it happening according to Model 2 (i.e., bottom up).

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It is for this reason that our latest distributed NSF center is called the Center for Climate and *Energy* Decision Making and is primarily focused on finding ways to decarbonize the energy system.

For that we primarily need analysis of cost-effectiveness, not B-C analysis.

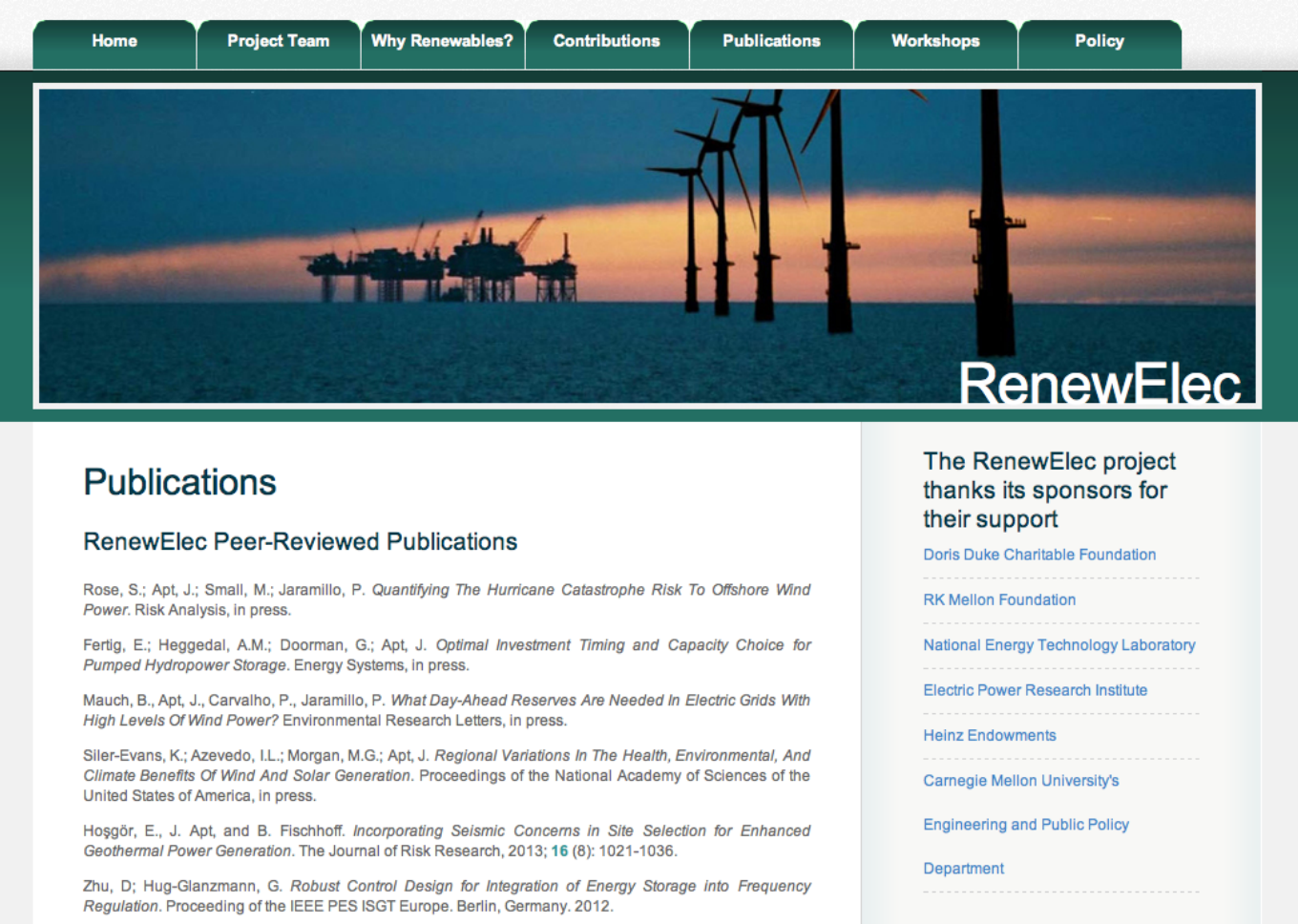
...are abatement supply curves for residential electricity.



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We've been doing lots of work on...

...understanding how to manage variable and intermittent renewables:



The screenshot displays the RenewElec website. At the top is a navigation bar with links: Home, Project Team, Why Renewables?, Contributions, Publications, Workshops, and Policy. Below this is a large banner image showing offshore wind turbines and oil rigs at sunset, with the 'RenewElec' logo in the bottom right corner. The main content area is divided into two columns. The left column is titled 'Publications' and lists 'RenewElec Peer-Reviewed Publications' with five entries, each providing author names and publication details. The right column is titled 'The RenewElec project thanks its sponsors for their support' and lists seven sponsors: Doris Duke Charitable Foundation, RK Mellon Foundation, National Energy Technology Laboratory, Electric Power Research Institute, Heinz Endowments, Carnegie Mellon University's Engineering and Public Policy Department, and Department.

Publications

RenewElec Peer-Reviewed Publications

Rose, S.; Apt, J.; Small, M.; Jaramillo, P. *Quantifying The Hurricane Catastrophe Risk To Offshore Wind Power*. Risk Analysis, in press.

Fertig, E.; Heggedal, A.M.; Doorman, G.; Apt, J. *Optimal Investment Timing and Capacity Choice for Pumped Hydropower Storage*. Energy Systems, in press.

Mauch, B., Apt, J., Carvalho, P., Jaramillo, P. *What Day-Ahead Reserves Are Needed In Electric Grids With High Levels Of Wind Power?* Environmental Research Letters, in press.

Siler-Evans, K.; Azevedo, I.L.; Morgan, M.G.; Apt, J. *Regional Variations In The Health, Environmental, And Climate Benefits Of Wind And Solar Generation*. Proceedings of the National Academy of Sciences of the United States of America, in press.

Hosgör, E., J. Apt, and B. Fischhoff. *Incorporating Seismic Concerns in Site Selection for Enhanced Geothermal Power Generation*. The Journal of Risk Research, 2013; **16** (8): 1021-1036.

Zhu, D; Hug-Glanzmann, G. *Robust Control Design for Integration of Energy Storage into Frequency Regulation*. Proceeding of the IEEE PES ISGT Europe. Berlin, Germany. 2012.

The RenewElec project thanks its sponsors for their support

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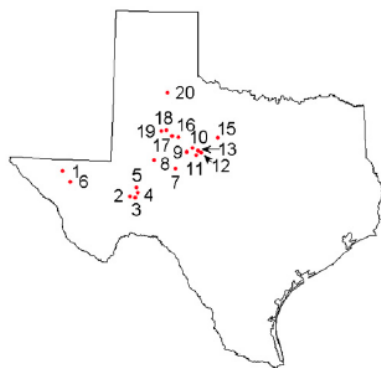
[Department](#)

Can't we smooth things out by connecting wind farms together?

The answer turns out to be "only a little."

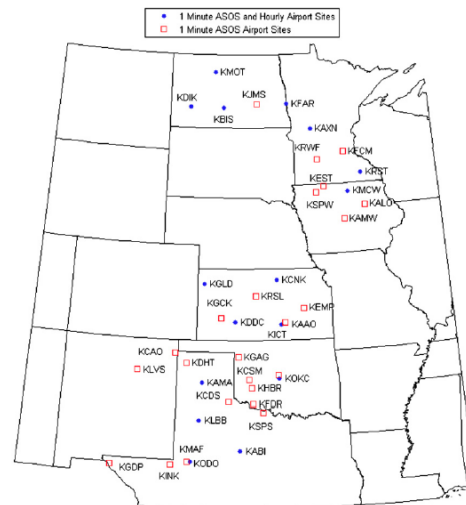
Jay Apt and his students looked first at the wind farms in Texas (ERCOT).

Then to make sure the results were not specific to just that region they also looked at data (scaled to hub height) from airports all across the mid-west.



15 min data

44



2 min. data



The variability of interconnected wind plants

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ABSTRACT

We present the first frequency-dependent analyses of the geographic smoothing of wind power's variability, analyzing the interconnected measured output of 20 wind plants in Texas. Reductions in variability occur at frequencies corresponding to times shorter than ~24 h and are quantified by measuring the departure from a Kolmogorov spectrum. At a frequency of 2.8×10^{-4} Hz (corresponding to 1 h), an 87% reduction of the variability of a single wind plant is obtained by interconnecting 4 wind plants. Interconnecting the remaining 16 wind plants produces only an additional 8% reduction. We use step change analyses and correlation coefficients to compare our results with previous studies, finding that wind power ramps up faster than it ramps down for each of the step change intervals analyzed and that correlation between the power output of wind plants 200 km away is half that of co-located wind plants. To examine variability at very low frequencies, we estimate yearly wind energy production in the Great Plains region of the United States from automated wind observations at airports covering 36 years. The estimated wind power has significant inter-annual variability and the severity of wind drought years is estimated to be about half that observed nationally for hydroelectric power.

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1. Introduction

Currently 29 of the United States of America have renewables portfolio standards (RPS) that mandate increasing their percentage of renewable energy, and the lower chamber of the United States Congress has enacted a federal renewable electricity standard (Database of State Incentives for Renewables and Efficiency, DSIRE, 2009; Waxman and Markey, 2009). Major electricity markets such as California, New York, and Texas expect wind to play a large role in meeting their RPS. As a result of the state RPS requirements and a federal production tax credit equivalent to a carbon dioxide price of approximately \$20/metric ton (Dobson et al., 2005), wind power net generation is currently experiencing very high growth rates (51% in 2008, 28% average annual growth rate over the past decade) in the United States (EIA, 2009).

Wind power's variability and fast growth rate have led areas including Cal-ISO, PJM, NY-ISO, MISO, and Bonneville power to undertake wind integration studies to analyze if their systems can accommodate significant (5–20%) penetrations of wind power (CAISO, 2007; DOE, 2008; EnerNex, 2006; GE, 2008; Hirst, 2002). Included in each integration study is how wind power variability can be mitigated with options such as storage, demand response, or fast-ramping gas plants. Some system operators are beginning

to charge wind operators for costs arising from the integration of high wind penetration in their system. In 2009, the Bonneville Power Authority (BPA) introduced a wind integration charge of \$1.29 per kW per month (~0.6¢/kWh assuming a 30% capacity factor), citing reliability risks and substantial costs encountered in fulfilling 7% of their energy needs with wind power (BPA, 2009).

Previous studies have shown that interconnecting wind plants with transmission lines reduces the variability of their summed output power as the number of installed wind plants and the distance between wind plants increases (Archer and Jacobson, 2007; Czigic and Ernst, 2001; Giebel, 2000; IEA, 2005; Kahn, 1979; Milligan and Porter, 2005; Wan, 2001). Kahn (1979) estimates the increased reliability of spatially separated wind plants, writing that “wind generators can displace conventional capacity with the reliability that has been traditional in power systems.” Kahn (1979) calculates the loss of load probability (LOLP) and the effective load carrying capability (ELCC) of up to 13 interconnected California wind plants.

Czigic and Ernst (2001) and Giebel (2000), in separate studies, show the correlation between wind plants decreases with distance. Each concludes wind power variability is reduced by summing the output power from spatially separated wind plants. Czigic and Ernst (2001) and Giebel (2000) both find that wind plant outputs are correlated even over great distances (correlation coefficient > 0).

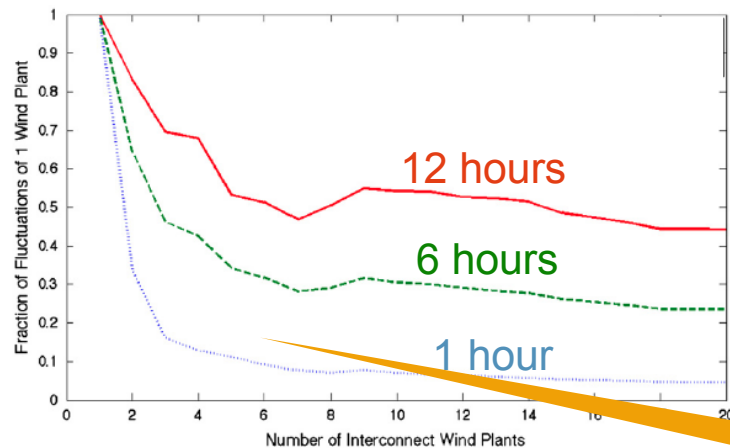
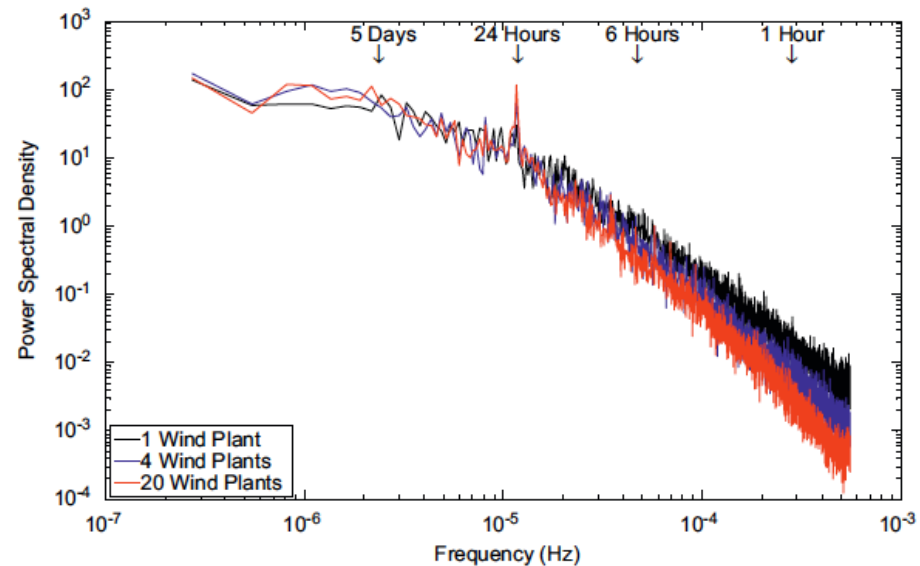
Milborrow (2001) shows a smoothing effect by calculating the output power change over a certain time interval (step change) of wind plants. He finds the 1-h power swing of 1860 MW of wind

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Texas results

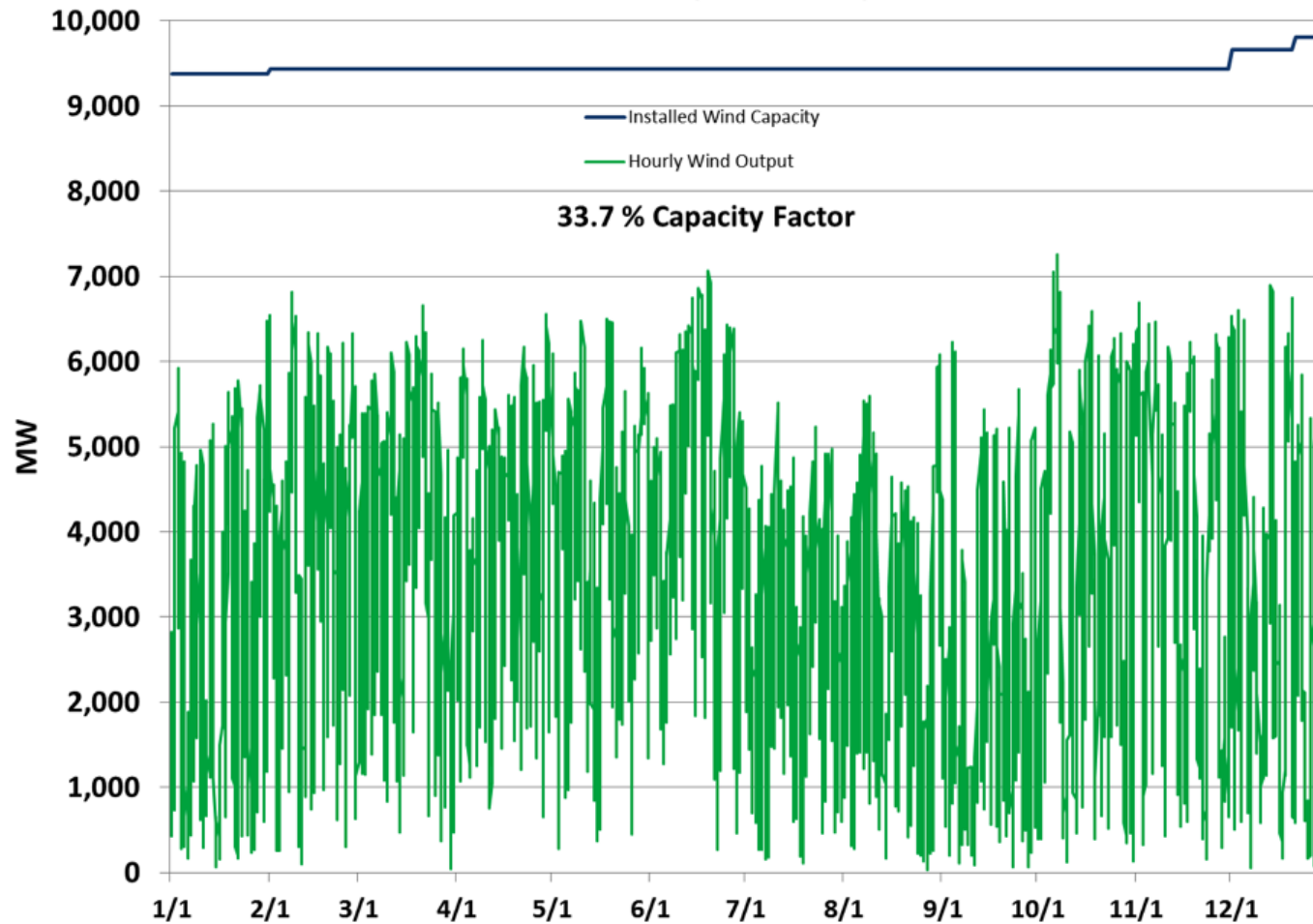
The maximum reductions in variability occur at the higher frequencies and diminish as the frequencies decrease until at 24 hours there is no reduction in variability.



This figure shows that amount of reduction in variability achieved as a function of the number of interconnected wind farms for frequencies corresponding to 1, 6 and 12 hours.

Note that after the first few wind farms are interconnected there is little additional reduction in the fluctuations.

Hourly wind output for *all* of Texas for the year 2011

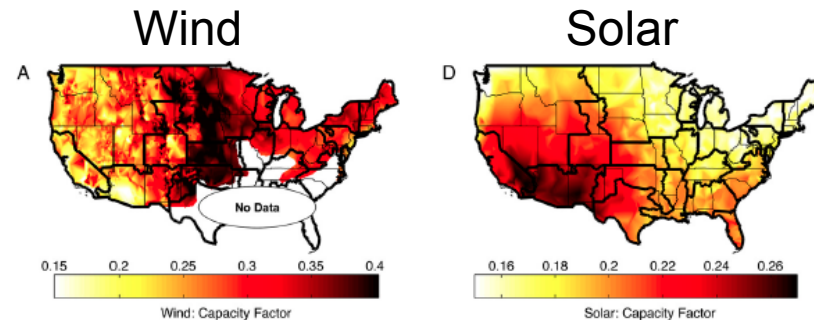


And, a reminder that because something is viewed as "green"...

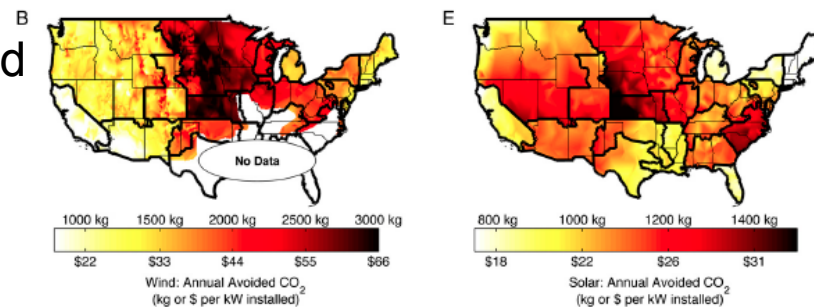
...we should not assume its impacts are uniform.



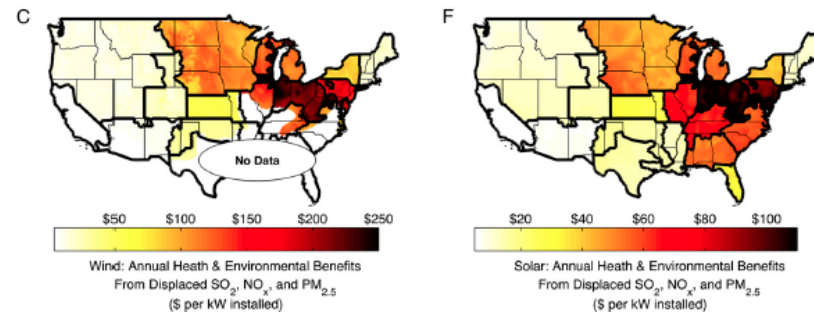
Energy:



Displaced CO₂:



Health benefit:



Source: Kyle Siler Evans, Inês Lima Azevedo, M. Granger Morgan, Jay Apt, "Regional variations in the health, environmental and climate benefits of wind and solar generation," *PNAS*, 2013.

Finally, here is work on SMRs

Expert assessments of the cost of light water small modular reactors

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Edited by William C. Clark, Harvard University, Cambridge, MA, and approved April 26, 2013 (received for review January 9, 2013)

Analysts and decision makers frequently want estimates of the cost of technologies that have yet to be developed or deployed. Small modular reactors (SMRs), which could become part of a portfolio of carbon-free energy sources, are one such technology. Existing estimates of likely SMR costs rely on problematic top-down approaches or bottom-up assessments that are proprietary. When done properly, expert elicitation can complement these approaches. We developed detailed technical descriptions of two SMR designs and then conducted elicitation interviews in which we obtained probabilistic judgments from 16 experts who are involved in, or have access to, engineering-economic assessments of SMR projects. Here, we report estimates of the overnight cost and construction duration for five reactor-deployment scenarios that involve a large reactor and two light water SMRs. Consistent with the uncertainty introduced by past cost overruns and construction delays, median estimates of the cost of new large plants vary by more than a factor of 2.5. Expert judgments about likely SMR costs display an even wider range. Median estimates for a 45 megawatt-electric (MWe) SMR range from \$4,000 to \$16,300/kW, and from \$3,200 to \$7,100/kW, for a 225-MW_e SMR. Sources of disagreement are highlighted, exposing the thought processes of experts involved with SMR design. There was consensus that SMRs could be built and brought online about 2 y faster than large reactors. Experts identify more affordable unit cost, factory fabrication, and shorter construction schedules as factors that may make light water SMRs economically viable.

nuclear power economics | technology assessment

Individuals, companies and other organizations, as well as governments, must make important decisions in the face of considerable uncertainty. Although we gather what evidence we can—as individuals, we choose where to go to college, who to marry, and whether to have children—we do this all in the face of at least some irreducible uncertainty. Similarly, companies choose to invest in major new technologies, and governments adopt tax and research and development policies, without knowing for certain all the consequences their decisions will have.

Our brains are not well-equipped to make decisions that involve considerable uncertainty. As extensive empirical research has now shown, we make such judgments using a variety of cognitive heuristics that, although they serve us adequately in many day-to-day settings, can result in overconfidence and bias that leads both lay people and experts astray when they address more complex and unusual problems (2, 3). Decision science (4–8) offers a set of strategies for improving how we make important decisions in the face of uncertainty.

In addressing such decisions, one should start with the best scientific, technical, and analytical evidence that is available. However, because such formal evidence often does not capture the full extent of what experts know, in addition to seeking informal expert advice, it is common in decision science to use formal methods to obtain systematic probabilistic judgments from experts who are intimately familiar with the current state of knowledge (9–11). For example, such methods have been used to characterize uncertainty about climate science (12, 13), the impacts of climate change (14–16), and the health impacts of environmental pollutants (17, 18). Of course, the same cognitive limitations that arise when we try to make unaided decisions also arise when experts attempt to provide probabilistic judgments (3). Too often, when seeking expert advice, little or nothing is done to limit overconfidence and reduce bias. Ubiquitous overconfidence (10) and the biases arising from cognitive heuristics, such as availability and anchoring and adjustment (2, 19–21), cannot be completely eliminated. However, well-designed expert elicitation can use a variety of strategies to help improve the quality of expert judgments (9–11).

Expert elicitation about emerging energy technologies that is deeply informed by careful technical analysis is still relatively rare (22). Here, we report the results of applying these methods to one such technology: integral light water small modular nuclear reactors (SMRs).

Why SMRs?

Morgan has argued that if aircraft were made and certified one at a time, in the way nuclear reactors have been built and certified in the U.S., “many travelers would find the level of safety unacceptable and air travel would be much more expensive... pilots and mechanics would have to be specially trained to operate each aircraft... many replacement parts would have to be custom made... [and] every time an aircraft experienced a problem engineers and managers would be unsure how to extrapolate the lessons to other aircraft...” (23). There is no way to mass produce gigawatt-scale reactors in the way that Boeing 747s and Airbus A380s are built. However, by adopting a smaller design, one that could be mass produced in a factory with high levels of quality control, and shipped to the field by road, rail, or barge, the nuclear industry might begin to look more like the aircraft industry. Because individual reactors would be smaller, the unit

Author contributions: A.A., I.L.A., and M.G.M. designed research; A.A., I.L.A., and M.G.M. performed research; A.A., I.L.A., and M.G.M. analyzed data; and A.A., I.L.A., and M.G.M. wrote the paper.

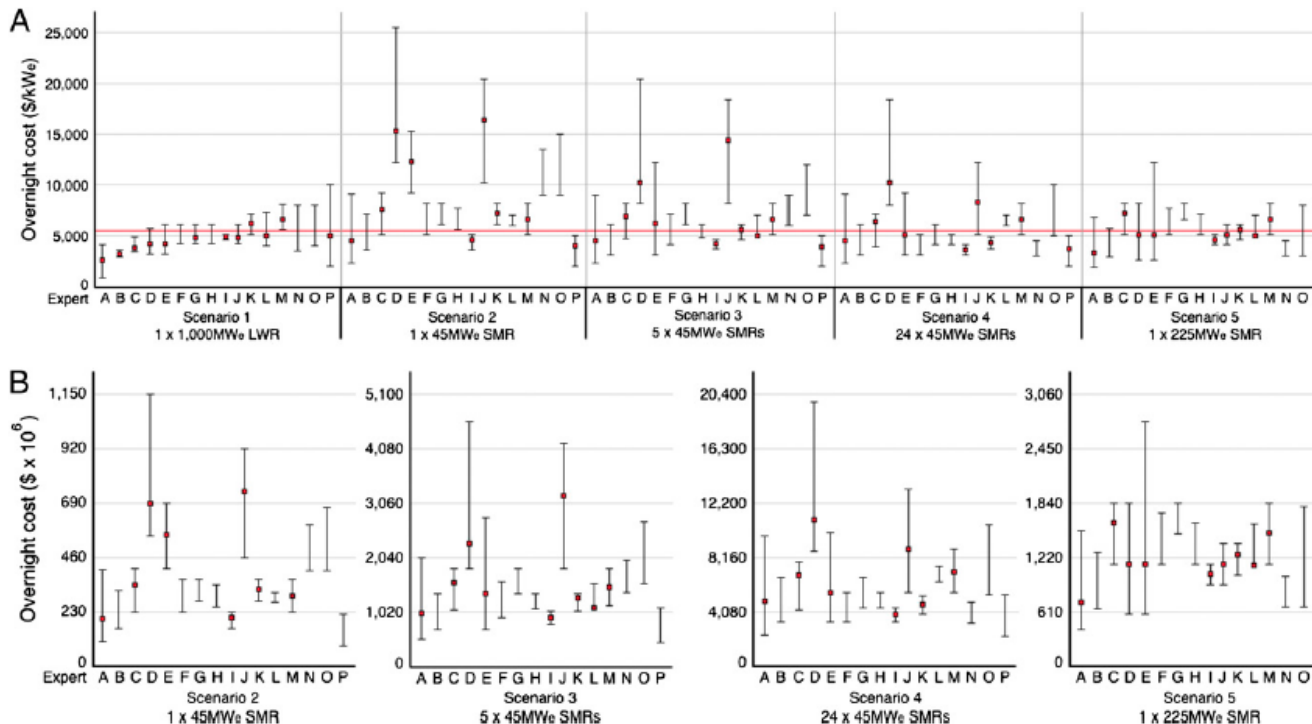
The authors declare no conflict of interest.

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www.pnas.org/cgi/doi/10.1073/pnas.1300195110



Back to 3 and 4

3. Choices by a nation as to whether and how much emissions abatement to undertake.
4. Choices by a nation as to whether or not to join an international agreement on emissions abatement.

As I have already argued, I do not believe that using B-C or similar methods to assess even the marginal value of the social cost of carbon makes sense.

However, if one framed things in game-theoretic terms (how much will others do, and in light of that, how much should I do), I guess I could imagine an analysis that used B-C ideas, although I am not persuaded it would be worth the time and effort that would be required.

Finally what about...

...including sea level rise in integrated assessment?

As some of you know, in the early 1990s, Hadi Dowlatabadi and I built the ICAM model that treated 2000 variables as uncertain and contained multiple switches that allowed us to explore the implications of alternative model functional forms. With an early version of ICAM...

...[we found] that the choice of decision rule plays a key role in the selection of mitigation policies, that given a decision rule, uncertainty in key variables can make it difficult or impossible to differentiate between the outcome of alternative policies and that the model parameters that contribute the most uncertainty to outcomes depend on the choice of policy, the discount rate and the geographical region being considered.

Hadi Dowlatabadi and M. Granger Morgan, "A Model Framework for Integrated Studies of the Climate Problem", *Energy Policy*, 21(3), 209-221, March 1993.

With ICAM 2 and 3, we found that...

- We could get an *enormous* variety of answers depending on the range of plausible assumptions we made about the structure of the model and which regional decision maker one considered.
- Rarely was any policy optimal for all regions.
- Rarely were any results stochastically dominant.

Our work has led us to believe that the first impressions gained from a 'global commoner' model may confuse more than they clarify. At the international level, at least a dozen different nations will make choices which could have significant climate implications. Many of those choices will not be made by single national decision-making authorities, but rather through the individual choices of millions of organizations and individual citizens, and they will be driven by local interests and conditions. This distributed decision making is one of the most fundamental characteristics of the climate problem.

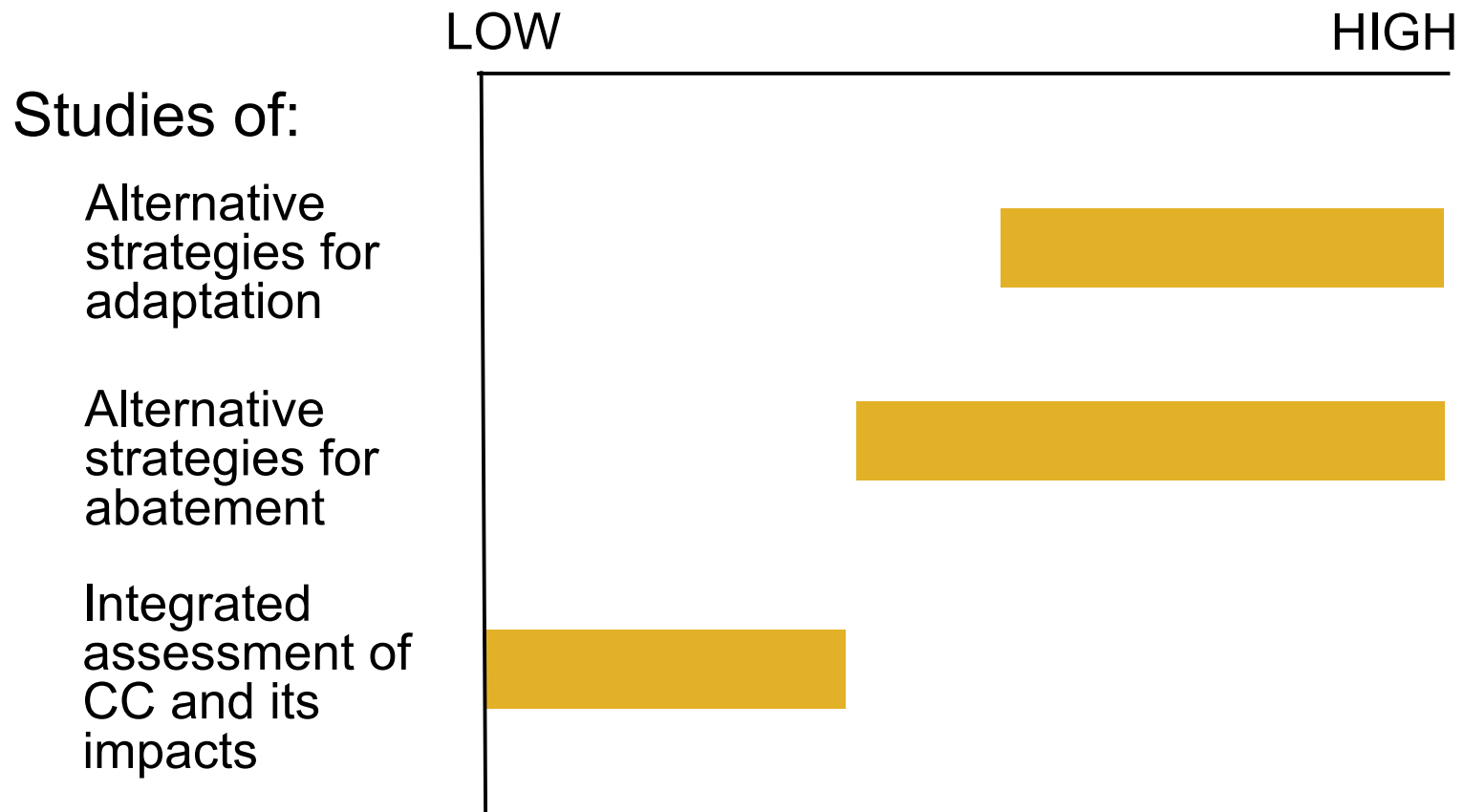
Doing IA was lots of fun...

...and intellectually very stimulating. We developed lots of insights which we wrote about in our papers - although it is not clear they had much impact.

However, because we found we could get a remarkably wide range of answers, because different regions often preferred different policies, and because over time we became increasingly persuaded that progress would occur via Model 2 (bottom up) rather than top down, with the resultant concentrations being an emergent property, not the result of explicit global policy design, we stopped and have moved on to work cost-effective abatement and adaptation.

For me, the key question is...

...who will do something different and consequential, in terms of either slowing climate change or moderating its consequences, as a result of the analyses we do?



End of my talk.

But...

I give the first opportunity to
comment to Hadi Dowlatabadi.

GHG Management from the top down.

The key thing...

...needed to implement
this model is integrated
assessment that
determines the target.

When Hadi looked at these slides he argued:

"Because this is a non-marginal change problem the IA will be wrong. The driver will be the economics of the system's change and its network effects. In my view, the change will be driven by those who profit, not those who suffer."

Perform an IA in order to determine the "optimal" level of abatement.

Through international negotiations get a global agreement in place that meets that level.

Get all major economies to "sign up" and implement coordinated policies to meet that level.

GHG Management from the bottom up.

The key thing...

...needed to implement
this model is emission
abatement supply curves
so that the world

When Hadi looked at these slides he argued:

"I think that this will not be driven by the concerns of GHGs but by energy and economic security. Framing this as climate change will continue because we will have periodic reminders in extreme events, not because we are naïve enough to think that actions will reduce these severe events - if we believed that, retreat would be in place right now."

Different parts of the world
get serious about reducing
emission of GHGs at
different times.

Each starts doing various
things to reduce emissions.

As they get serious,
national negotiations
work to coordinate
general abatement
regimes.

If and when we manage...

...to begin to get serious control of GHG emissions from major emitting countries, my money is on it happening according to Model 2 (i.e., bottom up).

At that point what will be most needed is clear evidence of what abatement strategies are most cost-effective.

It is for this reason that the center is called the Center for Climate Decision Making and is primarily focused on finding ways to decarbonize the energy system.

When Hadi looked at these slides he argued:

"This is not something that will fall out of the scenario I described above."

For that we primarily need analysis of cost-effectiveness, not B-C analysis.

End

In developing the ideas discussed in this talk, I have been fortunate to have generous support from the National Science Foundation (SES-9209783; BCS-9218045; SES-034578; SES-0949710 and others), the Electric Power Research Institute, the Gordon and Betty Moore Foundation, the Doris Duke Charitable Foundation, the MacArthur Foundation, the IRGC, Carnegie Mellon University and a number of others. Thanks also to my many colleagues and students, who have worked with me in these projects.